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FEASIBILITY STUDY TO DEVELOP A WATER DELUGE SYSTEM FOR CONVEYOR LINES TRANSPORTING HIGH EXPLOSIVES

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The feasibility of developing a prototype water deluge system capable of extinguishing fires in bulk flake explosives after a 60-lb detonation was demonstrated using off-the-shelf commercially available components. The basic elements of the system include: (1) a fast response UV fire detection tube and logic circuit, (2) a rupture disk water valve, (3) water piping, and (4) spray nozzles. The water deluge system was actuated less than 20 ms after 60-lb detonation located 25 ft from the detector. Narrow stream nozzles were used with each nozzle protecting 3 ft wide area ranging from 15 to 45 ft from the nozzle assembly. No blast damage was sustained by the prototype system in full-scale tests. Bench-scale studies included measurement of flame spread rates for flake TNT and

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evaluation of the UV detector tube sensitivity to TNT and Composition-B fires. The cost of a prototype system was estimated and it is concluded that substantial cost savings may result by the development of advanced technology components.

ABSTRACT

A program was conducted to design and experimentally test a rapid-response water deluge system for application to conveyor lines transporting high explosives. The program included both bench-scale studies and full-scale demonstration tests. The feasibility of developing a prototype water deluge system capable of extinguishing fires that develop in bulk flake HE explosive boxes after a 60-lb detonation was demonstrated.

Using off-the-shelf commercially available components a full-scale prototype water deluge system was designed and tested. The basic elements of the system included; (1) a UV detector and logic module, (2) a rupture disk water valve, (3) piping, (4) blast shields, and (5) water nozzles. To provide protection from blast exposure water supply lines were buried in the ground adjacent to the simulated conveyor line. Water spray nozzles were installed at ground level to maximize survivability. Narrow stream nozzles were utilized and each nozzle protected a 3 ft wide area ranging from 15 to 45 ft from the nozzle. The sprays were directed upward to a height of 7 ft. The time required by the UV detector to respond to an HE detonation was less than 5 ms. The time required for full operation of the rupture disk valve was less than 15 ms. No significant blast damage was sustained by the prototype water deluge system under full-scale test conditions. Bench-scale studies included the measurement of flame spread rates for flake TNT and Composition-B and measurements of the UV detector tube sensitivity to TNT fires.

The cost estimate of this prototype water deluge system can be reduced by using advanced technology components and by increasing the overall system response time.

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I. INTRODUCTION

Bulk explosives are moved from the receiving magazines to the processing areas either on continuous belt conveyors or on overhead suspension carriers. Other transportation systems have been considered, but for reasons of cost and simplicity, none of the systems appear to be competitive at the present time. In general there are two types of conveyor systems in operation, those transporting individual boxes of flake explosives separated by standard minimum distances, and those transporting loose flake utilizing a continuous or semicontinuous flow of material.

While in transit these materials pose a significant hazard potential resulting from unwanted fires or explosions. In the past, plant designers have not provided fire protection systems along conveyor line areas partly because of cost, and partly because of the assumption that adequate protection was maintained by using noncombustible building materials and safe separation distances. Unfortunately not all munitions plants are constructed using noncombustible materials; hence, a fire could propagate along the line into the processing areas. This propagation could be initiated by the burning of housing structures or by the dispersion of burning flake explosive particles under explosive blast loading. The problem is further complicated by restrictions placed on the activities of fire service personnel in fighting a conveyor line fire. Such personnel are normally instructed not to operate in the immediate fire area because of the possibility of further explosions. Since these problems will continue to exist, there is a need to develop a rapid-response fire protection system in order to isolate the fire and secure both the conveyor lines transporting high explosives and the plant processing areas.

Any fire protection system design involves: selecting an adequate detection system; choosing the best extinguishing agent; determining required application rates; and providing a delivery which can assure extinguishment. Cost, reliability, maintenance, freedom from false alarms, and response time factors affect each of the latter four areas. Because of the specialized nature of the problems incurred in fires involving the transportation of high explosives, standard fire protection engineering practices designed for industrial plants unnecessarily limit the choices of the plant designer. Therefore, a specialized fire protection system tailored to meet these special problems is needed.

This document outlines the results of a developmental program to provide munitions plant designers with an advanced fire protection system capable of solving these specialized fire protection engineering problems. The program was divided into four work tasks consisting of:

(1) A background study of existing conditions in munitions plants,

(2) The development of engineering design criteria to meet the specialized problems identified,

(3) Small-scale tests to develop specific information required, and

(4) A large-scale feasibility demonstrative test.

The program was limited to the use of off-the-shelf fire protection hardware items and to the problems of fire protection on conveyor lines transporting 60-lb boxes of flake high explosive from the plant unloading docks to the first plant processing area. The results of this program are outlined in the following sections.

II. BACKGROUND STUDY

A. Munition Plant Survey

A background study was made to define and document existing plant conditions. The major purpose of the study was to gather information concerning the following parameters:

- Conveyor types and lengths
- Maximum and minimum environmental temperatures
- Spacing of conveyor lines from walls and ceilings
- Type and quantity of explosive carried on line
- Type of blast relief designed into building structures
- Volumetric air flows along lines.

To perform this study plant surveys were conducted at munition production facilities in Parsons, Kansas; Burlington, Iowa; and Rock Island, Illinois. The Lone Star Plant was not surveyed because its conveyor lines were not in operation at the time of the survey. All the installations visited were originally constructed during World War II. Because of emergency conditions prevailing at the time, these facilities were designed and constructed using available materials including the extensive use of non-fire retardant wood.

1. Conveyor Types and Lengths

There are three general types of conveyor systems in use, rubber belts, steel rollers, and overhead suspension systems. The use of each system was apparently predicated on the material and equipment available in the area at the time of plant construction.

The length of the conveyor lines varies considerably. The longest length of line is approximately 2000 ft and the shortest line observed is about 300 ft. The length of most transitional sections (i.e., movement from ground level to an upper floor) is estimated to be about 200 ft.

The overhead suspension system consists of a trolly rail from which the explosive is suspended in aluminum buckets. In most installations the explosive moves down the center of the housing structure. For transitional sections, the lines are usually installed adjacent to the side walls. In the event of a detonation it is estimated that two types of shrapnel would be formed. Aluminum buckets used to contain the high explosive would tend to fragment, yielding high-velocity particles with estimated initial velocities ranging between 2000 and 4500 ft/sec. The overhead rail structures would be deformed by the blast wave with the possible formation of high-mass, low-velocity fragments. For this type of carrier the major damage mechanism would be anticipated to involve high-velocity aluminum fragments.

Conveyor systems using steel roller bars are usually located adjacent to one side wall with spacings of approximately 18 in. to the nearest wall and 8 ft to the furthest wall surface. In the event of a detonation in this system the major hazard would consist of the roller bars creating high-mass, low-velocity missiles. The protective side panels of the assembly are constructed of about 18-gage metal and would tend to deform rather than fragment upon blast loading.

Rubber belt conveyor systems are generally located either centrally down a corridor or adjacent to the side walls at a wall to line spacing similar to those used for steel roller lines. The major fragment hazard would consist of steel rollers together with the fire hazard posed by the use of combustible belt materials. A variety of

conveyor types are in use, each posing a different set of hazards under explosive loading. The average inside width of the structures housing the conveyor lines is 12 ft, and the average width of the conveyor belt is about 26 inches. None of the plants surveyed have fire detectors located along the conveyor lines although heat actuated detectors (HAD) were installed in the explosive processing areas. Fire doors or curtains are not generally used, and most of the exterior wall surfaces are either unprotected wood or asbestos shingles.

2. Volumetric Air Flows Along Line

The lines surveyed are located in open unheated structures. In some cases these structures are several hundred feet in length. The ends of the conveyor lines interface with either melt/pour or loading facilities. There are no forced or induced air flows. Most installations are open to the outside; and discussions with operating personnel indicated that the outside winds are a problem particularly in winter where the outside walls are not well sealed. At one plant location barrier curtains are placed at intervals to restrict fire spread and winter air currents. To summarize, the air flows in existing plants are highly variable ranging from static conditions to localized air velocities of 4 to 5 ft/sec. In most locations they are highly dependent upon outside weather conditions.

3. Type of Blast Relief

Most of the conveyor lines surveyed are housed in timbered structures. In some cases the exterior side walls are asbestos shingles, but in most cases they are wood siding. The lines surveyed can be characterized as not having any blast relief capability other than that inherent in a standard commercial warehouse or barn construction. Yet, because of the relatively light construction, the blast relief would be reasonably rapid.

4. Type and Quantity of Explosive Transported

The survey is limited to conveyor lines transporting flake explosives from a loading facility to the plant processing areas. Two types of explosives are transported, flake TNT and flake Composition-B. The explosive materials are transported in open cardboard boxes containing 60 lb of material. Minimum spacing between boxes is 12 ft and, depending on the activity of the plant, actual spacing varies from 12 to 20 ft for belt lines and is fixed by the hook spacings for overhead suspension lines. Thus the typical conveyor system carries 60-lb boxes of flake explosive at a spacing of at least 12 ft.

TABLE I. MINIMUM TEMPERATURES RECORDED THROUGH 1971

State	Temperature, °F
Iowa	–4
Illinois	–35
Texas	–23
Arkansas	–29
Georgia	–17

5. Minimum Environmental Temperatures

Because of the wide variability of local climates, water deluge installation requirements at each plant site must be reviewed individually. Table I summarizes the lowest minimum temperatures of selected regions in the United States.

For the specific plants surveyed the local minimum temperatures reported by the weather bureau were somewhat higher than those outlined in Table I. Based on this study it was concluded that the water deluge system should be capable of operating at –30°F, the lowest recorded temperature for the coldest area.

To protect the waterlines from freezing they should be installed at least 1 ft below the frost line. This minimum depth should be increased for soils consisting of gravel or loose soils and may be reduced somewhat for heavy clay soils. Because there is no water circulation in fire protection water mains, they must be installed deeper than normal water mains in the same area. Depending on geographical location, this depth varies from 2 to 10 ft. Since all types of soil are present in the facilities surveyed, soil core samples will be required prior to final design studies for a specific installation.

6. Water Service

No water service is generally available in the conveyor line areas. In the main plant processing areas the fire protection systems consist of sprinkler installations which are either actuated manually or by heat actuated

detectors (HAD). The pressure in the water mains is usually 80 psig. Although the number of installations surveyed is small there are limitations on the total water flow resulting from marginal plant input supply lines. The isolated nature of munition plants results in long line requirements for water service. In some installations, booster pumps may be required to maintain reasonable operating pressures.

B. Engineering Analysis

1. Nature of the Fire

Unwanted fires along a conveyor line can result from the action of either common ignition sources or explosions. Once started the fire may propagate along the line into plant processing areas causing major damage. The problem of designing a fire protection system to isolate and extinguish fires along conveyor lines transporting high explosives is unique in that detailed consideration must be given to reducing the effects of the fire spread mechanism. During an explosion, firebrands may be formed which can travel long distances. If these firebrands fall into and ignite boxes of high explosive, secondary explosions can occur. The result is an alternate fire-explosion-fire . . . type of fire propagation mechanism. Conceivably this type of fire spread could rapidly progress along the conveyor line into the melt/pour facilities. The control of fires resulting from this fire propagation mechanism requires different engineering designs than those used to control fire spread over a contiguous bed of fuel.

2. Detection System

The detection system must be able to rapidly and accurately detect and respond to either a fire or explosion hazard. Technically this can be accomplished either by using a multicomponent detector system consisting of two or more sensors, each selected for its ability to sense a specific hazard, or by using a single sensor sensitive to both fire and explosion. In terms of overall system cost and simplicity, a single detector capable of responding to both hazards would be preferred. In terms of reliability and the prevention of false alarms, multicomponent systems must be considered. The final choice of whether a single or multicomponent system is employed depends on an engineering trade-off between reasonable costs and reliability.

In order to determine the existence of a fire, a sensor must perceive a physical or chemical change in the environment which is uniquely related to the existence of a fire in the area under surveillance. Possible environmental changes resulting from a fire which can be used for this purpose include:

- Temperature rise
- The presence of combustion products
- Radiant energy emission.

Selection of the type of fire detector most suitable for a given application depends principally upon the speed of detection required, which, in turn, depends upon the nature of the fire and the potential hazards involved without rapid extinguishment. If a fire develops rapidly, such as a flaming fire in a box of flake explosives, it can be detected in a relatively short time because of the great changes taking place in the local environment. On the other hand, if a fire develops slowly, as would be the case in smoldering combustion involving Class A material, detection of the incipient fire is difficult and the smoldering action could continue for hours before detection. For either type of fire it is important that the evidence be clear and unmistakably identified if false alarms are to be avoided.

a. *Rate of Temperature Rise Detectors.* The presence of a fire may be determined by monitoring the rate of temperature rise in the local environment. A reliable device for performing this task is the heat actuated detector (HAD). This device is widely used in industrial plants and in some munitions production facilities. The HAD consists of a pressure chamber containing a pressure sensitive switch and a capillary bleed valve. A rapid rise in external temperature causes the pressure to rise in the chamber more rapidly than it can be relieved by the bleed capillary; hence, the pressure switch is activated. Diurnal fluctuations in temperature are automatically balanced by

the bleed valve. When sited above the fire area the maximum response time of this device is several seconds. Other devices that monitor the rate of heat rise, such as thermocouples, are also available.

The aforementioned detectors are not suitable for the proposed application. First, their response time is highly dependent on proper siting. For instance, a fire in a box of flake explosive traveling on a conveyor line would be no problem to detect since placement of detectors at selected intervals would secure a response time dependent on the rate of travel of the conveyor. However, a fire occurring along a stationary line would have a low probability of detection since the detector would not necessarily be in close proximity to the fire. Secondly, even at best their time of response is slow relative to blast wave effects. Although the pressure switch would probably be explosion sensitive, the reaction time of the switch is long compared to blast wave propagation velocities; and it would be expected that in the event of a detonation the detectors and/or their cabling would be subjected to severe damage before they could function.

b. Combustion Product Detectors. Combustion product detectors are normally classed as either optical devices depending on the obscuration of a light beam, or ionized particle devices depending on the unbalancing of a circuit in an ionization chamber. Optical devices (or smoke detectors) are relatively insensitive and require the development of a substantial fire prior to their initiation. Advances in detection systems based on obscuration effects include the development of laser systems for use in warehousing application. These are subject to false alarms whenever obstruction of the optical beam occurs. These effects would restrict the application to monitoring the upper portions of the structures housing the conveyor lines and the response time would be slow. For this reason, optical detectors are not considered further.

Ionization particle detectors depend on the formation of combustion products which may be too small for the human eye to see as smoke. Most smokes contain particles 0.01 to 1.0 μm in diameter and become visible only when sufficiently concentrated. In relatively clean atmospheres the background concentration levels average about 10^7 particles/cm^3. These concentration levels rapidly increase to 10^{14} to 10^{17} particles/cm^3 over even a small fire. Because of these large changes, the ionization chamber detectors are very sensitive and can reliably and rapidly detect small fires. This type of detector is uniquely capable of detecting the presence of smoldering combustion.

The nature of the voltage curve produced by a fire gas in an ionization detection device varies depending on the type of fuel and fire severity. For most fires the voltage curve reflects an initial rapid rise, followed by a tapering off and irregular signals. It is believed that the steep part of the curve is associated with the arrival of highly mobile invisible combustion particles in the detector chamber, and the decay signal is probably controlled by the effect of larger smoke particles. The sensitivity and speed of response of these detectors are directly relative to the rate of voltage rise. For the Pyrotronics F-6 detector the trip voltage is normally set at 2 to 3 volts. However, this voltage can be lowered to 1.0 volts with reasonable reliability for fast response detection. For a cotton batting fire initiated by a hot wire with the detector placed 2 ft above the fire, the rate of rise was experimentally found to be 42 V/min, thus providing a maximum response rate of about 1.5 sec.

The response time of the ionization detector at a given installation is fundamentally limited by the mechanisms which transport particulates from the fire or pyrolysis zone to the detector. These processes involve either natural or forced convection and may require several seconds to several hours depending on fire severity and the siting of the detector. Because of the requirements for exposed siting, the ionization detectors would not be expected to survive a blast wave following a detonation. Further, in the event of a fire the response time would be relatively slow being limited by natural or forced convection transport processes. Because of this slow response, the ionization detector was not selected for experimental testing.

It was noted, however, that ionization chamber-based detection systems such as the Pyrotronics F-6 low voltage dual chamber can uniquely detect the presence of a smoldering fire. A smoldering fire may be initiated by faulty electrical wiring, spontaneous combustion in Class A material, a hot belt on the conveyor line, and a number of other common fire ignition sources. Since these ignition sources may result in the development of a major fire, the fact that the detector may not respond *rapidly* does not necessarily imply that an ionization detector should not be used as part of a multicomponent detection system.

c. Radiant Energy Detectors—Infrared Detectors. Radiant energy sensors can be divided into two classes, infrared sensors and ultraviolet sensors. A radiant energy sensor can rapidly respond to flaming combustion

provided there is a direct line of sight from the fire to the detector. There are a number of commercial units which are blind to background radiation but which respond to the appearance of a flame. Each flame source is characterized by a spectral signature, i.e., distribution of energy in specific emission bands. For many fires the principal emission results from blackbody emission of hot carbon in the infrared, the line broadened sodium-d lines in the visible, and several highly specific emission bands in the ultraviolet. The total intensity of the flame depends on flame area and diameter; and the level at which a detector will respond is limited by its sensitivity and the strength of radiation it receives. Both UV and IR sensors can respond to strong input signals within milliseconds. Unfortunately the response time of the detector system is considerably longer if false alarms are to be avoided.

The problem of distinguishing signal from noise is most acute for infrared sensors because of the multiplicity of stray signal sources that can trigger the circuitry. There are two general types of IR sensors that have been devised to reduce these problems. The most common type distinguishes the signal from noise by monitoring an AC signal produced by the sensor resulting from a flame flicker. Most types of Class A fires have flames which fluctuate at a frequency between 5 and 25 c/sec. No data are available on the flicker frequency of TNT or Composition-B. A real fire condition is identified by the sensor whenever the output signal corresponds to a frequency in the 5 to 15 Hz range. Strong infrared signals which might result from a number of other sources simply raise the DC voltage level and do not result in false triggering. Because of the need to reliably establish the low frequency AC signal, the overall response time can be no faster than about 1 sec. This dependence on flame flicker is inherent in all the off-the-shelf commercial units surveyed.

Advanced infrared sensors based on selective discrimination between two or more selected IR wavelengths are also under development. Characteristically these detectors can sense and operate in the 10 to 100 ms. range. The principle of operation is similar to that of a two or three color optical pyrometer. For reliable sensing of fire it is necessary to utilize a three band system in which a central optical band is compared to two other bands, one at a longer wavelength, the other at a shorter wavelength. An explosion suppression program at the US Bureau of Mines has recently demonstrated the effectiveness of the three color IR system, but because the program was limited to using off-the-shelf components this detector was not tested. Also, present costs for the prototype systems available are relatively high. Further work using this type of system may be warranted.

d. UV Detectors. Flames also produce both specific and continuous radiation in the ultraviolet region. Although the total amount of energy produced at short wavelengths is small their quanta energies are high and can be used to activate photomultiplier tubes. A number of UV detector tubes have been developed based on Gieger Muller tubes. A survey of manufacturers indicates that there are currently three corporations producing the basic tubes necessary for fire detection. Two manufacturers are in the United States, the Edison Industries and the Detector Electronics Corporation, the third is Japanese. The Edison tube consists of two parallel plates which view the fire from an end-on configuration. The signal output strength is limited because of the geometry of the detector. However the tube is reliable and distributed widely for use in fire protection applications. The Detronics tube consists of two plates, one an open grid network, the other a solid plate. The side of the open grid plate is oriented toward the fire resulting in a much higher sensitivity for this type of tube primarily due to its increased exposure area. This tube is produced commercially and is readily available and solar blind. The tube operates on a narrow bandpass and is sensitive to radiation between 1800 to 1900 A.

The response time of the Detronics tube to pulsed radiation is about 1 ms, being limited by deionization processes. The response time for the total detector system is somewhat longer depending on the confidence level desired. To prevent false alarms by stray energy sources, such as lightning strokes, a discrimination circuit must be used. In normal operation this circuit is set to count a predetermined number of tube pulses before an alarm condition is indicated. This number varies depending on application. When set at a five count frequency, the tube must pulse a minimum of five times resulting in an inherent delay time of about 5 ms.

For a five count discrimination logic circuit, consideration must be given to the time required to actuate switching relays. For most coil operated relay systems the closing time depends on the time to achieve field coil saturation. Typical values for the time required for coil saturation are 200 ms. Solid state circuitry is available which can provide much more rapid switching and closure. A survey of manufacturers' specifications indicated the required switching can be accomplished in much less than 1 ms using solid state relays. Because of its sensitivity and speed of response the Detronics tube and control system was selected for further experimental testing.

3. Water Distribution System

a. *Water Valves.* One of the limiting factors in developing a rapid-response water deluge system is the response time of the valves connecting the main waterlines to the individual water distribution lines. Therefore an automatic valving system is necessary to provide water to the fire zone. A review was made of the response times for solenoid, pneumatic, and rupture disk valves. The survey was limited to 2- and 3-in. valves for use with water having an initial pressure differential of 100 psi. For this purpose the valve actuation time was defined as the time from the delivery of an electrical sign to the valve to the time that the line is fully opened.

Typical values for fast actuating solenoid valves ranged from 750 to 1000 ms. The differences between solenoid and pneumatic actuation times were minimal. These data apply to off-the-shelf hardware, and it is estimated that a reduction of actuation time to 300 and 500 ms for 2- and 3-in. valves respectively could be achieved using advanced technology components.

Typical actuation times for rupture disk valves were 15 to 30 ms. Again a reduction in response time can be made by using advanced technology components. It is estimated that a 2 to 5 ms response time could be achieved by using a 600-μs squib and a special shaped charge explosive to rupture the burst disk diaphragm.

The selection of the type of valve to be used involves an engineering trade-off between fast reaction time, cost, and reliability. For this design study, major emphasis was placed on speed of response and reliability. When properly installed both the solenoid and rupture disk valves have high reliability. Since the rupture disk has no moving parts, it is particularly simple. The major disadvantage of the rupture disk valve is that it requires one or more detonators which present a possible security problem. The major advantages of the solenoid and pneumatic valves are their cost, commercial availability, and the ability to cycle from a closed-open-closed configuration. This cycling capability is of particular importance if it becomes necessary to deactivate a system in the event of a pipe rupture. The major disadvantage of the solenoid valves is their relatively slow response time. After detailed evaluation, the rupture disk valve system was selected for experimental testing because of its fast response time.

The specific water valve selected for further testing was a Fite rupture disk valve which was developed for use on fast-response fire protection systems. This valve is manufactured in sizes ranging from 2 to 24 inches. The valve is actuated by rupturing a scored stainless steel diaphragm using a shaped charge explosive installed on the upstream side. The explosive is protected from water damage by a waterproof plastic coating. The explosive is initiated using a standard Du Pont squib. For applications requiring high reliability two squibs are used to insure actuation. The major operating parameters of the valve, such as the actuation time, depend upon two factors: (1) the delay time in the squib, and (2) the specific operating conditions upstream and downstream of the valve. Typically the delay time in the squib is about 9.5 ms for the detonation and can be reduced to 600 μs using specialized detonators. The opening time of the valve depends on the depth of scoring of the rupture disk and is estimated to be in the range of 2 to 5 ms. Since previous applications have not included a fully loaded, wet pipe, water deluge system, specific data was not available regarding the precise valve opening times or optical scoring.

The valve system selected is manufactured in two general series corresponding to whether it is capable of being reloaded on site. The valves tested were of the A-60 series provided with a dual detonator for improved reliability.

b. *Protection of Water Supply System From Climatic Extremes.* The explosive ordnance plants surveyed were geographically located in the north central portion of the United States. Most of the currently operating plants are located either in this region or in southern states. In all cases the conveyor systems were installed in unheated buildings. No problems are anticipated associated with high temperatures such as might occur in the summer except for installations located in desert regions where vaporization of exposed water at the nozzles might result in the formation of salt deposits for inorganic freezing point depressants or a concentration of flammable organic water solutions.

In cold climates a freezing point depressant must be used for wet pipe systems in all lines that are located above the frost line. Both organic and inorganic freezing depressants used for this purpose were evaluated.

The most widely used inorganic freezing point depressant is Type 1 or Type 2 calcium chloride containing pipe corrosion inhibitors. Other common inorganic systems include: lithium chloride solutions; lithium chloride/calcium chloride solutions; and lithium chloride/sodium chromate solutions. The most common organic-based freezing point depressants include glycerine, propylene glycol, ethylene glycol, and diethylene glycol. In order to meet low temperature requirements in cold climates high concentrations (50 percent of organic depressants) must be used. Since there are a number of cases where the organic depressant resulted in an additional fire hazard, the use of organic depressants is not recommended.

The following table outlines the quantities of $CaCl_2$ required for protection of unheated lines at temperatures of 0°F and below. Because the freezing point depressants shown above are widely used in industrial fire protection systems, information regarding their use was readily available from military specifications and procedures. After a review of this information it was concluded that the present military standards and specifications are adequate for this application.

TABLE II. CALCIUM CHLORIDE FREEZING POINT DEPRESSION OF WATER

Temperature, °F	Quantity Required, lb/gal.	
	Type 1	Type 2
0	2.83	2.17
−10	3.38	2.55
−20	3.89	2.90
−30	4.37	3.21
−40	4.73	3.44
−50	4.94	3.59

c. Water Line Construction. In hazardous areas NFPA consensus standards recommend the use of steel pipe and fittings. At one of the plants surveyed an inspection was made of a production facility that had been damaged by a heavy blast. Damage to the piping was minimal. However, the water deluge system had been only partially operative because of a fracture in the cast iron line fitting behind a blast wall. The NFPA recommendations should be followed with the use of either steel or welded fittings.

In order to determine pipeline sizes for selected flows, standard engineering calculations for hydraulic flow can be used. In most practical cases these procedures use empirical correlation parameters in which the pressure drop in the lines is estimated by using friction loss factors. Figures 1 and 2 provide data necessary for determining fluid flow in pipe flows for 2-, 2-1/2-, and 3-in. diameter pipes.

The effect of the blast wave on the waterlines is difficult to evaluate except experimentally. Three major damage mechanisms can result in the inactivation of the system. First, a ground shock can propagate in the concrete floor and result in displacement of the waterlines or failure in their supports. The second mechanism involves interaction of the waterlines with the direct and reflected blast shock waves. Finally, fragmentation of metal components in the conveyor lines can result in formation of high-velocity shrapnel which can puncture the waterlines. The vulnerability of the waterlines to fragment impact can be estimated using data available from the literature for penetrations of steel plates by high-velocity fragments. The distance of penetration is dependent on the initial velocity of the primary fragment. Particle velocities at the charge surface are about 5000 ft/sec which represents a maximum. Realistic fragment velocities are estimated to fall in the 1000 to 1500 ft/sec range. Figures 3 and 4 can be used to estimate the required pipe wall thickness and sand depths necessary to protect the waterlines. The blast wave overpressure is estimated at 400 psi for an explosion on the conveyor line directly opposite the blast shield.

d. Water Deluge—Droplet Size. For intense fires large spray droplet sizes are more effective due to their ability to penetrate the fire plumes. Correlation was made of data presented by Yao and Kalelkar (*Fire Technology*—November 1970) with droplet size curves made available by Spraying Systems Company for a typical internally impinging nozzle. These curves indicated that the delivery of fully effective 3-mm or larger diameter droplets was about the same regardless of pressure. Increased nozzle pressure while delivering more total gallons would not be expected to increase extinguishing effectiveness, particularly against the sort of flame plumes expected from burning explosives. The calculated values are shown in Table III. Based on this data it was inferred that a 15-deg or 30-deg typical spray nozzle could not deliver the maximum effective droplets. Therefore, the optimum nozzle

TABLE III. CALCULATED DROPLET SIZE DISTRIBUTION

Pressure, psi	Total Flow, gpm	% Droplets Above 3 mm	Effective gpm	Non-Effective gpm
10	8.3	68	5.6	2.7
40	15.8	48	7.6	8.2
100	24.3	20	4.9	19.4

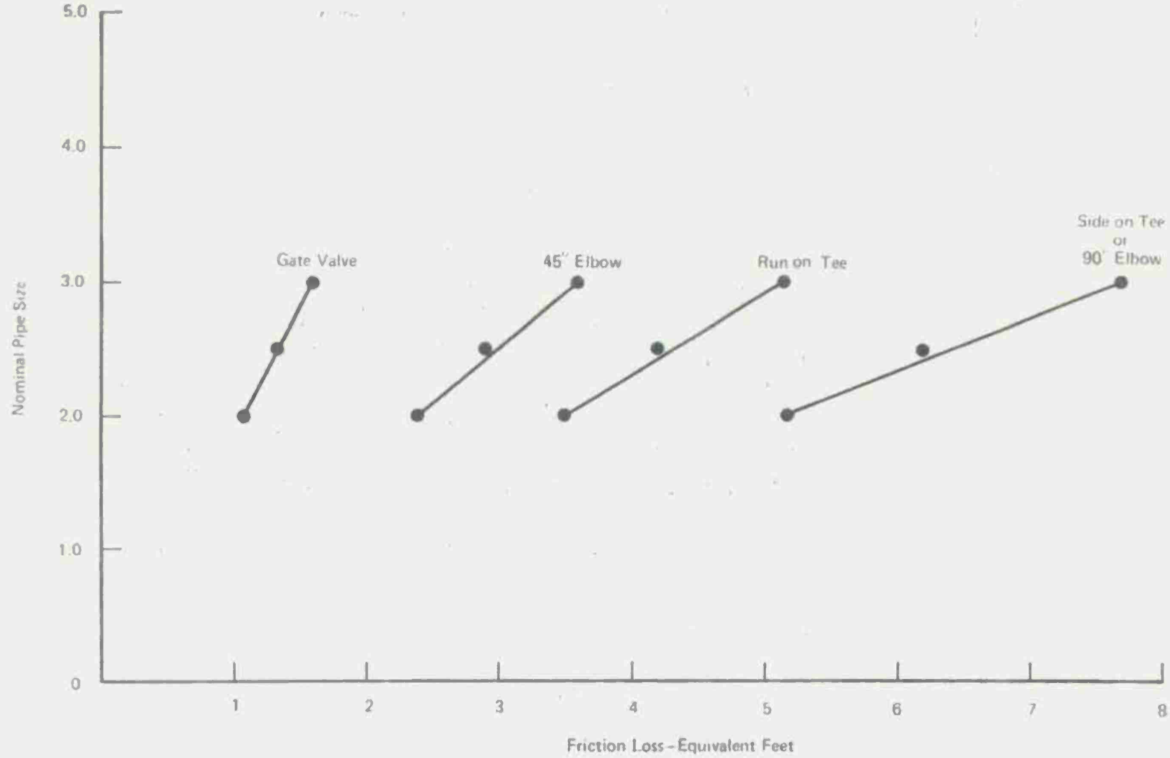


FIGURE 1. FRICTION LOSS FOR SELECTED PIPE FITTINGS–
FINAL WATER DISTRIBUTION SUBSYSTEM

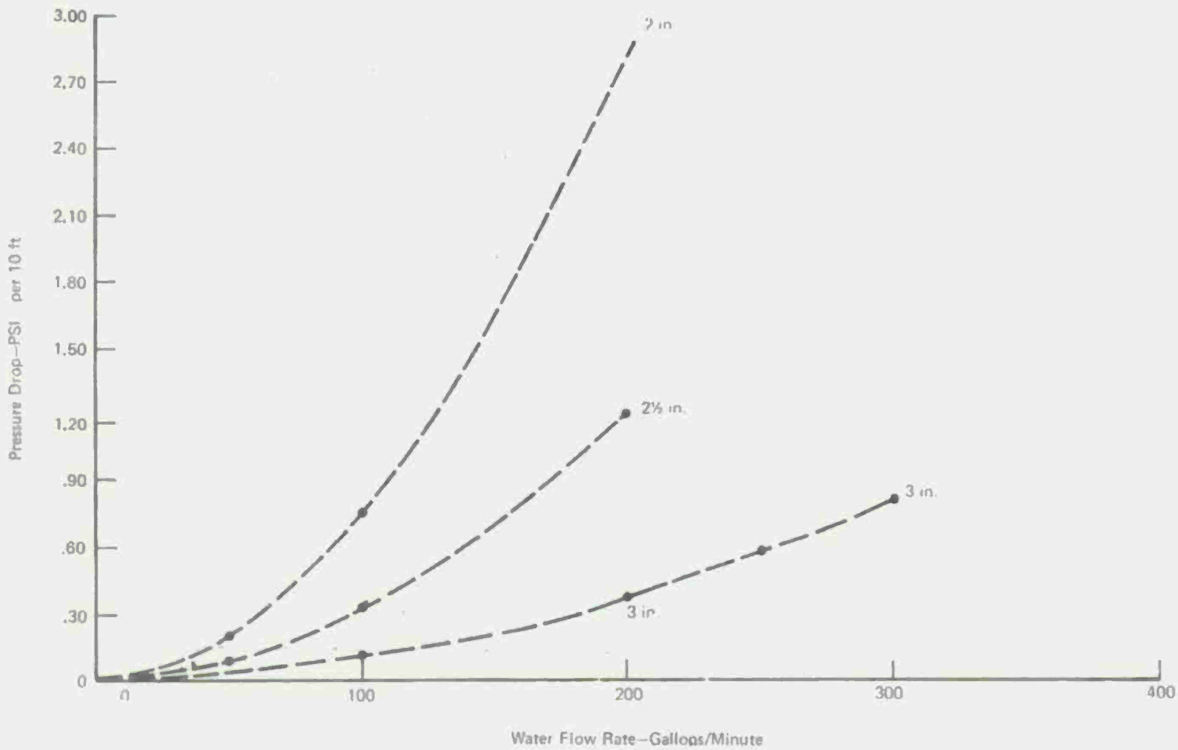


FIGURE 2. PRESSURE DROP VS WATER FLOW RATE FOR SELECTED PIPE SIZES

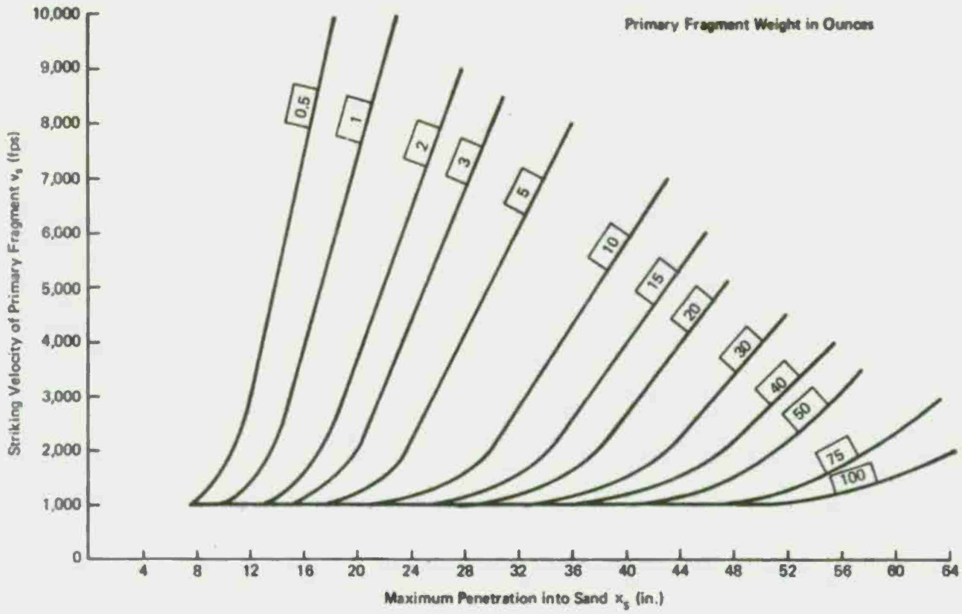


FIGURE 3. FRAGMENT PENETRATION THROUGH SAND

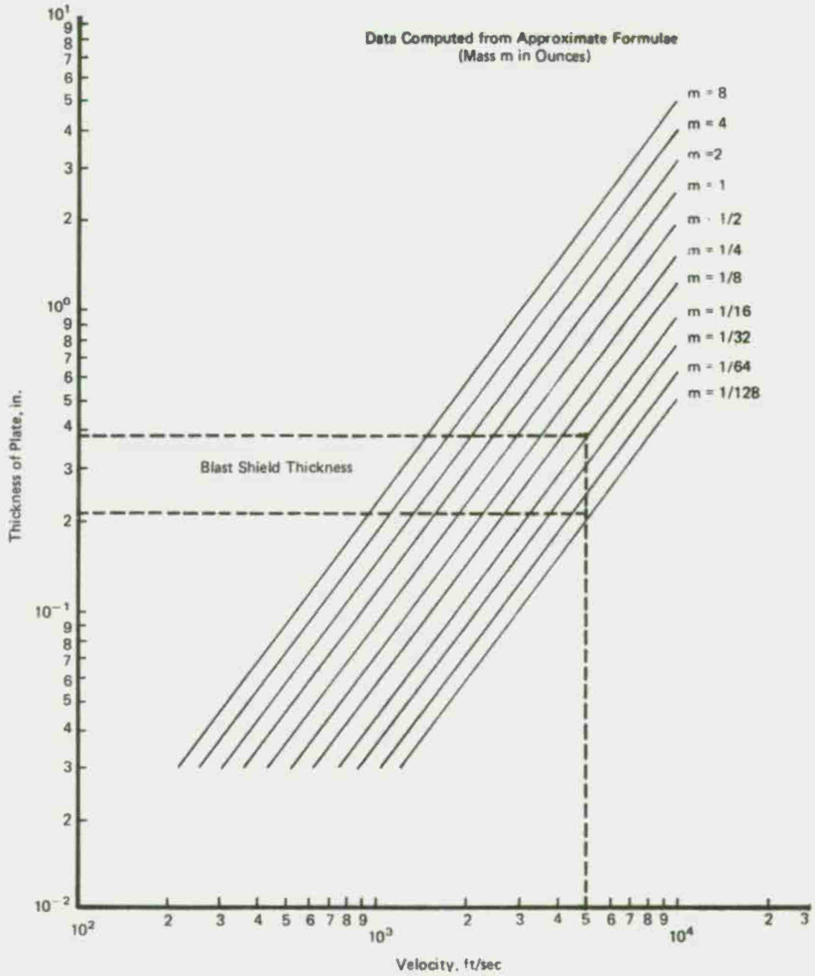


FIGURE 4. DEPTH OF PENETRATION OF MILD STEEL
VS STRIKING VELOCITY

design would be a solid stream nozzle, operated at maximum stream range so as to break up into large droplets from normal turbulence. This simplifies the design by using the normal 80 psig system pressures while, at the same time, avoiding excess fine droplet production. A plot of flow rate versus pressure head for selected 0-deg angle nozzles is given in Figure 5. It is noted that a possible application of this large droplet solid stream nozzle could be the redesign of existing deluge systems at melt pots, etc.

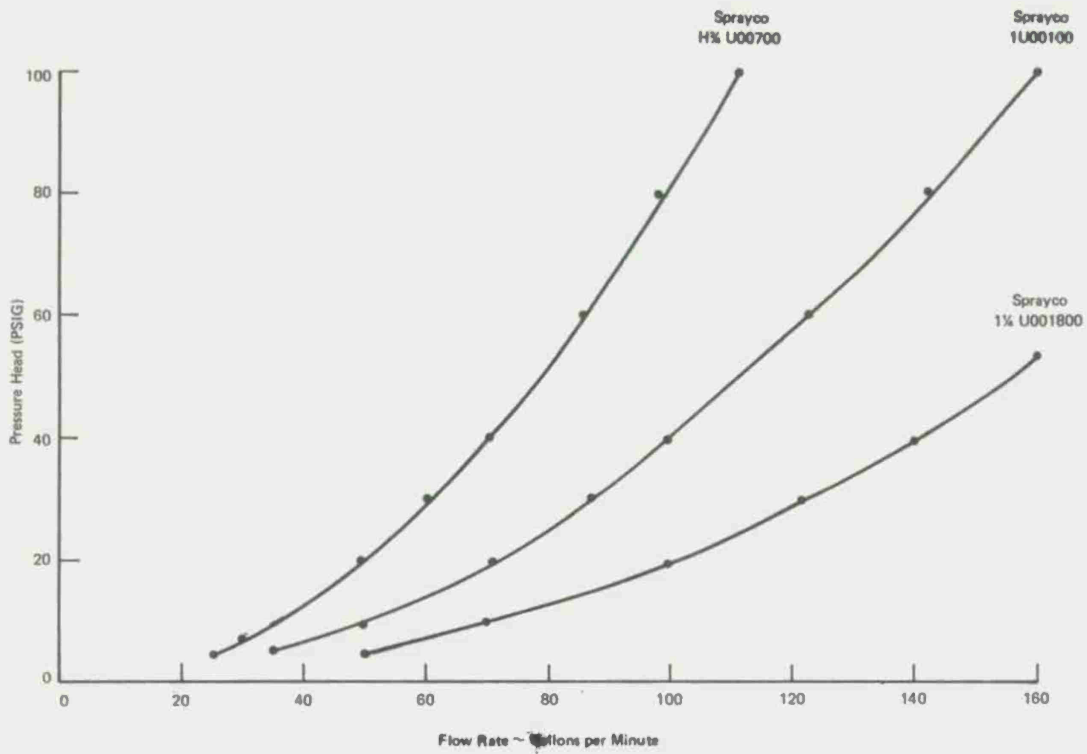


FIGURE 5. FLOW RATES FOR SELECTED 0° ANGLE SOLID STREAM NOZZLES

C. Design Criteria

It is possible that a fire incident might be initiated with a detonation, but the most likely case is that of ignition of explosive material with the possibility of subsequent explosions, depending upon the degree of confinement. A fast response fire protection system could quench such fire and avoid any major damage. A possible choice is an ultraviolet detection system operating in the milliseconds range with controllable time delay set to keep accidental triggerings to an irreducible minimum. The optimum detector spacings depend on the allowable flame area and emission signature properties of explosive flames.

Several candidate extinguishing agents such as water, inert gases, the Halons, and dry chemicals can be considered. The nature of the burning materials requires the extinguishing agent to have high cooling rates and the ability to penetrate intense flame plumes. Of the candidate extinguishing agents, water is most satisfactory. There are no standards for water application rates for explosives, but the consensus indicates about 0.5 gpm/ft^2 is an acceptable value. This value is a trade-off between what might be required and the costs of delivering larger amounts to the scene of the fire.

The normal industrial practice is to protect plant areas with overhead mounted spray nozzles with circular distribution patterns. For ammunition plant ramps, such an arrangement is subject to damage by explosion. The concept best suited to a system which must operate after an explosion is based on waterlines located at or below

ground level. The water supply would come from the plant systems, normally at or about 50 to 80 psig. A signal from the detectors would open a rupture disk or solenoid to actuate a wet pipe system. In cold climates a freezing point depressant such as lithium chloride must be added to the water–after operation, the system is drained of fresh water, and the solution replaced. The nozzles would be a narrow stream type, directed slightly upward from both sides of the path of explosive travel in opposing directions. The nozzle spacing and angular position are determined by pattern tests for probable conditions. In case of pipe rupture, excess flow valves are necessary to prevent excess loss of water from deactivating the system.

Based on the considerations outlined in the previous sections together with discussions with the project monitor, specific design criteria were established. The major criteria are summarized below:

- Detector Response Time . . . . 10 ms
- Valve Actuation Time . . . . 20 ms
- Shielding Armor for Nozzles . . . . . . 400 psia Overpressures
- Exposed Waterline Shielding . . . . . 1/2-oz Fragments Traveling at 1500 ft/sec
- Lowest Temperature . . . . -30°F
- Water Application Rate . . . . 0.5 gal./ft^2/min
- Component Availability . . . . Off-the-Shelf Hardware

Using these criteria a prototype system was selected. The prototype system consisted of the following specific components:

- Detector–Detronics UV Detector with Solid State Logic Control Circuitry;
- Valve–Fite Series A-60 Rupture Disk Valve with Dual Detonators;
- Pipe Size–2- and 3-in. (Schedule 80) Pipe;
- Blast Shields–1-in. Steel Plate;
- Water Nozzles–Narrow Stream Nozzles.

D. Failure Mode Analysis

In order to identify the possible modes of failure, a failure mode analysis of the proposed prototype system was performed by W. Coffey. An overall schematic diagram outlining this mode of analysis is given in Figure 6. Since numerical values of the probability for failure and success for each step were not available, a detailed hazard analysis was not attempted. It is interesting to note that two of the possible failure modes were operative in the first two large-scale field tests.

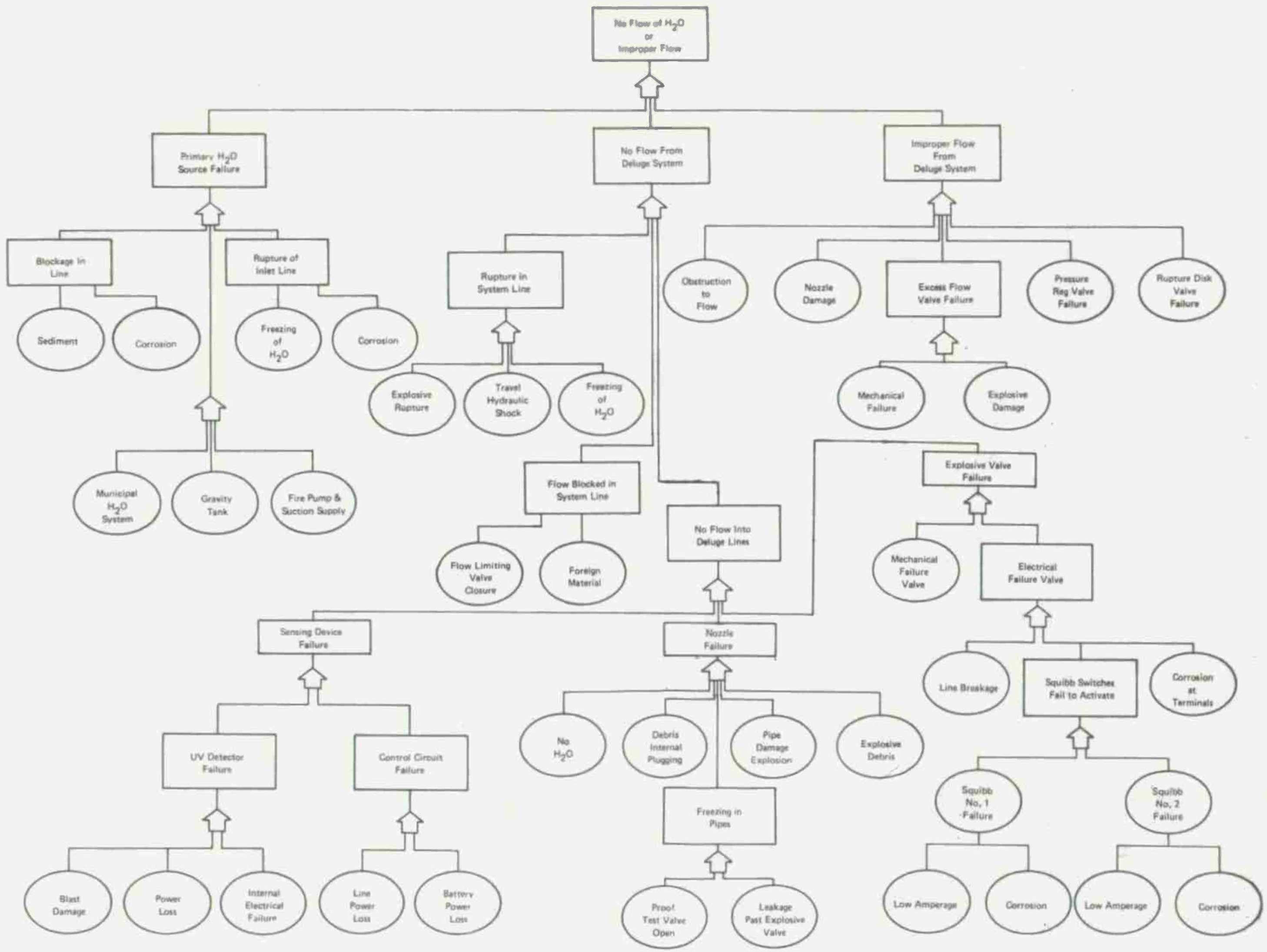


FIGURE 6. FAULT TREE ANALYSIS–WATER DELUGE SYSTEM

III. SMALL-SCALE TESTS

A small-scale test program was conducted to obtain information about the burning properties of flake high explosives not available from the literature and to verify designs developed for the prototype system. These tests included: (1) the evaluation of the operating characteristics of the UV Detronics detector for application as an explosion and fire detector for flake TNT and flake Composition-B; (2) the determination of flame propagation rates across thin beds of flake TNT; (3) verification of blast wave impact; (4) the determination of the rate of burning of flake explosives in a cigar mode burn configuration; and (5) evaluation of the relative application rate available from narrow stream nozzles.

A. Detector Response Tests

Detector response characteristics to 1-lb C-4 high explosive tests were conducted to determine whether the Detronics UV fire detection system could function in a dual capacity for both fire and explosion detection. For this purpose the detector was placed at a height of 6 and 25 ft away from 1 lb of C-4 and the charge detonated. Measurements were made of the rate of detector pulses and the duration of the effective emission. Two tests were conducted, one using a bare explosive and a second in which the explosive was contained in a cardboard box. The detector discrimination circuit was set to provide electronic signal actuation after 10 counts. A Tectronix 551 dual beam oscilloscope was used to monitor individual pulses and to determine the total system actuation time. The results are shown in Figure 7 and Table IV.

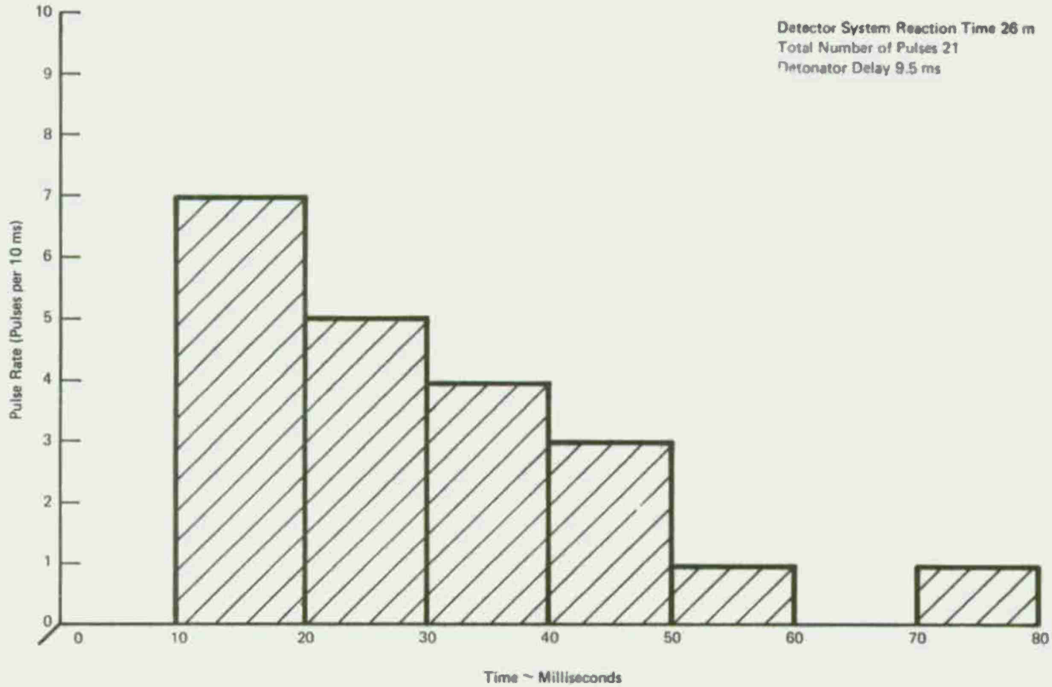


FIGURE 7. DETECTOR RESPONSE FOR 454 (1-LB) C-4 CHARGE

The experimentally observed delay time in the detonator was 9-1/2 ms. After 26 ms, 10 pulses had accumulated and the output relay from the detector logic circuit was actuated. The time required for activation of the water deluge system was 16 ms after initiation of the blast. Pulses were emitted over a period of 74 ms and were characterized by a relatively high initial frequency followed by a rapid decline. Based on these results a discrimination count requirement greater than 21 pulses would not trigger the water deluge system. An estimate of the shock wave velocity indicated

TABLE IV. PULSE RATE FOR TOTAL SYSTEM

Time Interval, ms	Number of Pulses
0-10	0
10-20	7
20-30	5
30-40	4
40-50	3
50-60	1
60-70	0
70-80	1

that the blast wave had traveled approximately 12 ft at the time the system was actuated. It was concluded that the system would have functioned before blast wave damage to the detector could have occurred and that hardening of the detector tube is unnecessary.

B. Blast Shield Tests

To verify the adequacy of the blast shield design, a series of quarter-scale tests were conducted. Quarter-scale models of the blast shields were fabricated in accordance with design calculations, and these models together with piping were installed on an old concrete block (see Figure 13). Three tests were conducted. For the first two tests, a 1-lb charge was used consisting of 0.8 flake TNT and a 0.2-lb C-4 booster. The charge was cubical with a C-4 booster located at the center of the cube which was then placed in a cardboard box. The third test used an unconfined spherical C-4 charge. In order to establish an absolute line base a break wire was placed around the outside of the charge to monitor the drop of a DC applied voltage.

The test arrangement is shown in Figure 8. Two blast shields were installed on the concrete slab with two lengths of 1/2-in. pipe to simulate the water deluge system. The shields were constructed of mild cold-rolled steel. The pipe was galvanized iron. Both blast shields were fastened to the concrete with lead lag anchor bolts. The explosive was suspended 1 ft above the floor and placed directly opposite the center of the front face of one blast shield at a spacing of 8.5 in. and at an angle of approximately 30 deg from the second shield at a spacing of 18 inches.

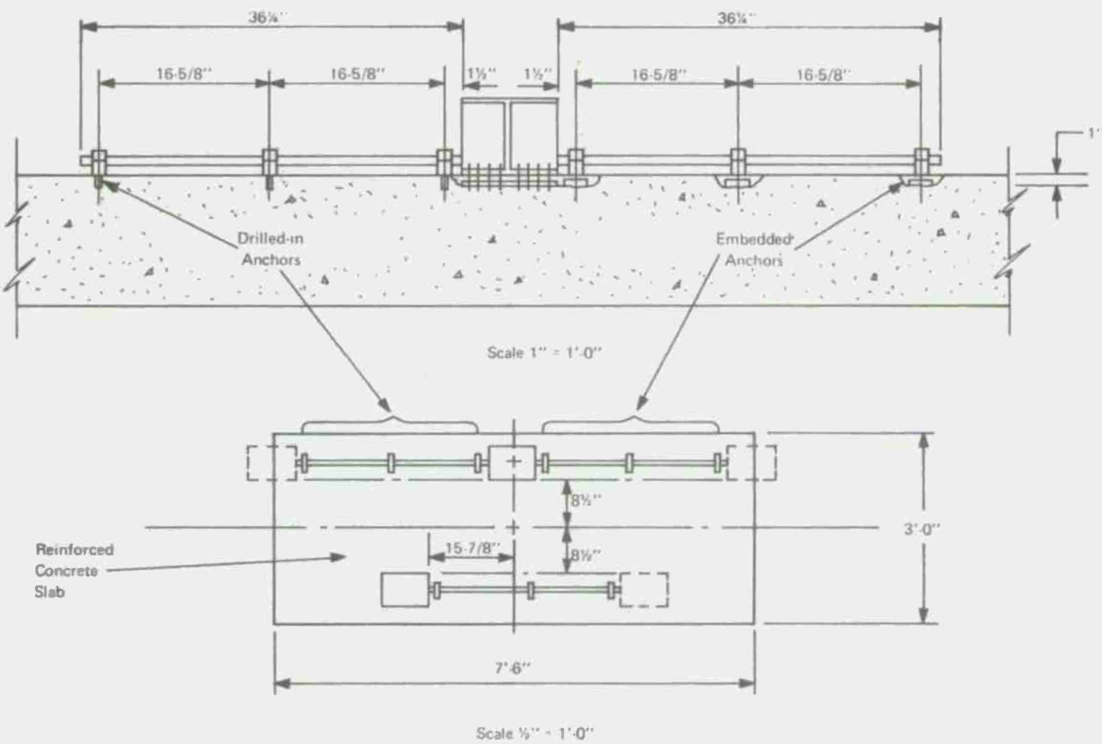


FIGURE 8. TEST ARRANGEMENT FOR SMALL-SCALE BLAST TESTS–SPRAY NOZZLE PROTECTIVE SHIELD DESIGN

In these tests no structural damage was sustained to the deluge system water nozzle shield or piping as a result of any of these tests with the exception that the lead anchor bolts pulled away from the concrete slightly. No

deflection or bending of the water pipe occurred, and there was no apparent difference between the flake TNT and a spherical C-4 explosive charge of the same weight. Based on these results it was concluded that the blast shield design is conservative and that blast shields can withstand the overpressures expected.

C. Fire Characterization Tests

1. Flake TNT

A hot wire ignitor was used to start a fire in flake TNT. This ignitor consisted of a coiled nichrome resistance heating wire embedded in the top of the TNT surface. Ignition was very slow and a relatively long time was required for the flame to fully engulf the surface.

a. Water Deluge Extinguishment Time. Table V shows the time required for extinguishment of a fully engaged 100 in.^{2} TNT fire. These times vary between 2 and 17 sec for the fires studied. The 17-sec extinguishment time was the result of the delay in extinguishment of a Class A fire, i.e., the cardboard. Because the fire is a liquid pool fire for a combustible liquid having a high melting point, the water deluge is effective at low application rates.

TABLE V. TIME TO EXTINGUISHMENT FOR 100 IN.^{2} FLAKE TNT FIRES–WATER DELUGE*

Test No.	Range, ft	Weight TNT, grains	Pressure, psig	Elevation, deg	Time, sec
1	30	5603	20	20	2
2	40	5600	20	20	3
3	40	7000	20	20	3
4	40	7000	30	20	5
5	23	7000	20	20	10
6	45	3420	20	20	17

*Data for 1-1/4-in. U001800 Spraying Systems Nozzle–Water Application Rate Variable. For Average Flow Rate See Figure 5.

b. Detector Sensitivity Tests. A series of 14 tests were made to evaluate detector response rate using a 1-in.^{2} flake TNT fire surface. This area was arbitrarily chosen for a design base fire. Four additional tests were performed in order to determine the effects of total fire area on detector response. Based on these tests it was found that the Detronics ultraviolet detector is about 200 times more sensitive to burning TNT than to gasoline. This detector operates in a narrow spectral response range centered between 1800 and 2400 Å. Examination of the spectral emission characteristics of individual fire gases would suggest that specific emission from the delta electronic transition of hot NO may be the principal factor accounting for this high sensitivity.

The detector sensitivity is a function of four major factors: (1) the combustible fuel, (2) the location of the detector, (3) the exposed area of fire and (4) in some cases the thickness of the fuel bed. Because of the viewing angle of the detector with respect to the fuel the correlation between size of fire and the detector response is strongly nonlinear. However, it was observed that this nonlinearity provides a "straight line" on a log-log graph. Three sizes of TNT fires were evaluated ranging from 1 to 64 in.^{2} in exposed surface area. The effect of fuel bed depth was independently investigated by varying the total weight of flake TNT for a given exposed surface area.

A 70 grain TNT fire having an exposed surface of 1 in. produces average detector responses of 15 and 70 counts/sec at distances of 60 and 20 ft, respectively. For 140 grain fires the detector sensitivity increases by a factor of two, apparently as a result of increased fuel bed depth. A similar thickness effect was observed during larger fire studies. Using these data, detector response criteria can be established. The minimum count necessary to prevent false alarms is five counts. Assuming that extinguishment action is started when the fire area involved is 1 in.^{2} the detector/controller system response time is 1 sec for a detector located 50 ft from the fire and reduces to 70 ms at 20 ft. For 0.21-in. fuel beds the response time is 125 ms at 30 ft. Using this data, a detector/controller system response time on the order of 100 ms could be obtained using detectors located every 30 ft. The time delay in providing a signal from the controller to an explosive valve is much shorter and would not affect overall system performance.

c. Rate of Flame Spread. The question of whether 100 ms is a reasonable response time can be answered by comparing the rate of growth of the fire to the reaction time of the fire protection system. Using the

TABLE VI. FLAME SPREAD RATE–FLAKE TNT

A. From 1-in.^{2} Average Count Rate to 16-in.^{2} Maximum Count Rate

Test 1	1.5 sec/in.^{2}
Test 2	3.0 sec/in.^{2}
Test 3	2.0 sec/in.^{2}
Test 4	2.0 sec/in.^{2}
Test 5	2.0 sec/in.^{2}

B. From 1-in.^{2} Average Count Rate to 64-in.^{2} Maximum Count Rate

Test 6	1.5 sec/in.^{2}
Test 7	0.7 sec/in.^{2}

TABLE VII. BURNING RATE OF COMPOSITION-B (3/16 IN. FLAKE)

Inches	Seconds	Seconds/Inch
	Test 1[b]	
1	8	–
2	60	52
3	120	60
	Test 2[b]	
1	40	40
2	110	70
3	180	70
4	300	Flame Out
	Test 3[a]	
1	45	45
2	80	35
3	135	55
4	155	Flame Out
	Test 4[a]	
1	30	30
2	58	28
3	87	29
4	145	Flame Out

[a]Average–cellophane wrapper...40 seconds per inch

[b]Average–cellophane wrapper plus paper...60 seconds per inch

*Loose pack density 0.60 gms/cm^3.

experimental data in Table VI, the growth rate of the fire can be estimated by comparing the time required to reach a maximum count rate for fires of varying sizes. For 0.09-in. fuel beds, the development of the 1-in. TNT fire to maximum intensity requires approximately 12 sec. For 0.21-in. fuel beds the time is increased to approximately 22 sec. For 0.09-in. fuel beds having an exposed area of 16 in.^{2} the time of development is about 20 sec, and for 0.21-in. beds the average development time is 38 sec. For a single 64-in.^{2} test, the time of development is 90 sec. Using these data a rate of growth of the fire is 1.0 and 0.95 in.^{2}/sec for the transition from 1 in.^{2} to 16 in.^{2} and 64 in.^{2} TNT fires, respectively. The fact that close experimental agreement is observed is probably accidental, and it can be concluded that the rate of fire growth is probably in the range between 0.5 and 2 in.^{2}/sec. Compared to the available response time of the fire extinguishment system this is a very slow flame propagation rate.

2. Flake Composition-B (0.5-cm Chips)

The burning rate of flake Composition-B was measured for cylinders 1.5 cm (0.59 in.) in diameter by 10 cm(4 in.) in length. The average downward burning velocities were determined to be 16.5 sec/cm (60 sec/in.). The burning resulted in the formation of a liquid surface melt 0.30 cm (1/8 in.) in thickness and it would appear that a liquid fuel fire was involved. The relationship between flake size and burning rate was not determined. Visual observation indicated a clear burning fire in sharp contrast to TNT.

Composition-B flake approximately 0.5 cm (3/16 in.) by 0.3 cm (1/8 in.) in thickness was packed into a cellophane cylinder 1.5 cm (0.6 in.) in diameter and 11 cm (4 in.) in length. The cylinder was placed in an upright position and ignited at the top surface using an electrical ignition wire. The rate of burning was determined by visually observing the rate of progression downward. Three tests were conducted using a thin cellophane wrapper. One test was conducted using a paper wrapper. The average rate of downward progression of the flame was 42 sec/in. for the cellophane wrapper and 60 sec/in. for the paper wrapper. The burning was uniform with a stable flame front. Only limited sideburning of the cellophane wrapper occurred which apparently did not affect the burning rate. The flame was quenched on one test and the surface of the remaining explosive examined. A melt zone approximately 0.3 cm in thickness was observed and no evidence was found to indicate significant side burning. The average density of the flake bed was 0.6 gms/cm^3.

IV. PROTOTYPE DEMONSTRATION TEST

A. Introduction

A series of three field tests were conducted to determine the feasibility of the engineering design concepts developed for a rapid-response water deluge system capable of surviving the blast wave from a 60-lb box of high explosive. The results of these tests indicate the feasibility of using these concepts to develop an advanced water deluge system for application to present and future munitions plant modernization programs.

To conduct these tests a field facility was developed at Camp Bullis. A schematic drawing of the overall test site is shown in Figure 9. The test facility consisted of a concrete floor, a series of fast-response fire detectors (Figure 14), a water supply system (Figure 15), a fast actuating blast valve (Figures 16 and 17), a water distribution system and a wood platform to simulate a conveyor line (Figures 18 and 19). Each test used a nominal 60-lb box of Composition-B as a donor. Time-0 was established by a break wire embedded in the C-4 booster charge. Test No. 1 had a 60-lb second acceptor box located approximately 10 ft from the donor. Test Nos 2 and 3 used a box of combustibles (paper and rags) weighted to 60 lbs as an acceptor. Based on the results of the first two tests changes were made in the design of the system to improve overall system reliability. A fully operational water deluge system was demonstrated on Test No. 3.

B. Instrumentation

1. Photography

Still photography was used to document the overall test setup and blast damage. Real time motion picture photography (24 fps) was used to document all cold flow water and fire tests. High-speed motion picture photography was used to document blast wave effects and water deluge action during the blast survival tests. Four high-speed cameras were used consisting of two Redlake Hi Cams, a Redlake Lo Cam, and a Traid. Two of the cameras, the Traid and the Lo Cam, were positioned 325 ft from the side of the simulated conveyor line. The two Hi Cams were positioned 450 ft from the conveyor line and provided end-view coverage. At each position two lenses were used to provide a combination of overall and close-up coverage. For the "end-on" Hi Cams one camera was operated at a framing rate of 440 fps and used a Cinemator telephoto F3.0 Eglett 3-in. lens. The second camera (Hi Cam 400 ft No. 7787) was operated at 200 fps and used a Soligol F1.35, 150-mm ITV lens. The second camera was also provided with an internal timing generator in order to establish an absolute time-base at 100 Hz. For the side-view cameras, the Lo Cam Redlake (Model 50) was set at 200 fps and used a Anastigmatic F2.7 102-mm lens. All motion picture cameras were electrically operated using portable gasoline engine-driven power supplies.

2. Electronic Instrumentation

Two dual beam oscilloscopes recorded four channels of high-speed data. One, a dual beam Model 55 Textronix Oscilloscope was used to monitor the pulses received from the UV detector at the 25 ft location together with the extinguishment signal sent to the blast valve from the fire detection system. A sweep speed to 5 ms/cm provided a total recording time of 50 ms. The second oscilloscope was used to monitor the total number of pulses received from all detectors and the pressure transients in the waterline at a point 12 ft downstream from the rupture disk valve. A sweep speed of 10 ms/cm provided data for a total of 100 ms after the time of the explosion.

C. Experimental Results

1. Test No. 1

A 60-lb box of Composition-B was placed at one end of a wooden table 42 in. high and 16 ft long, centrally located on the concrete floor approximately 4-1/2 ft from a blast shield. Detonation of the Composition-B was effected by a 1/2-lb booster charge of C-4 placed in the center of the loose flake. An acceptor box containing

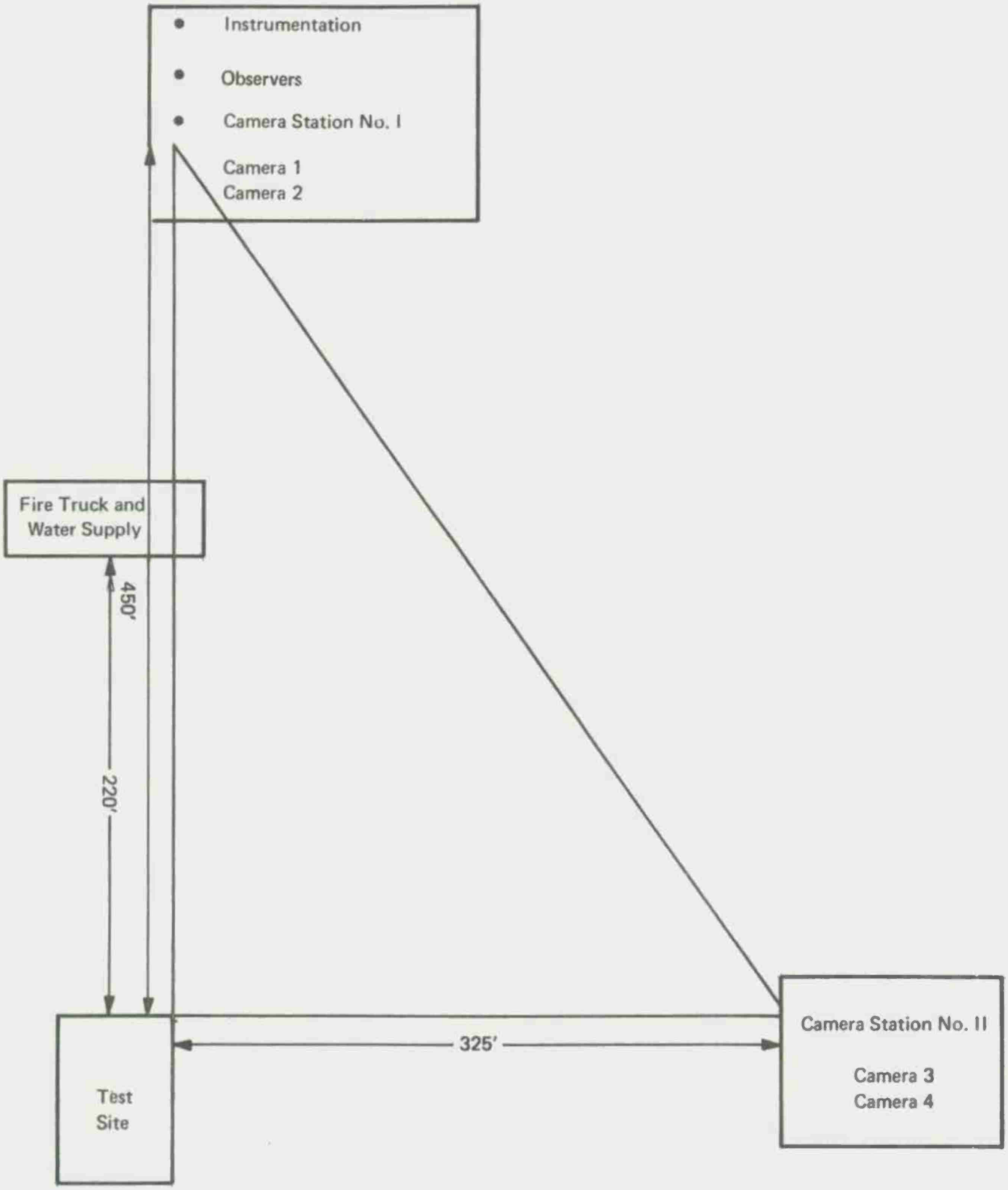


FIGURE 9. SCHEMATIC DIAGRAM OF OVERALL TEST SITE

60-lbs of Composition-B was placed 10 ft from the donor and the C-4 charge detonated. Although the test was considered a success the water deluge did not operate. A postmortem examination established that an excess flow valve located too close to the blast valve had closed causing the malfunction. The blast/fire detection system used a 6 pulse discrimination logic circuit. Using this circuit, a signal was sent to the explosively activated water valve within 4 ms after the detonation, see Figure 10 and 11. A pressure transducer located 12 ft from the valve indicated the onset of flow for a period of 50 to 75 ms after which flow was terminated. An examination of the pressure trace suggested that the rapid actuation of the explosive water valve resulted in the closure of the excess flow valve. Damage was sustained by two blast shields used to protect the spray nozzles but otherwise no damage was sustained to the water distribution system, Figure 20. No damage was sustained by the detector units. A fire was developed in loose explosive from the acceptor box and in the combustible materials used to simulate the conveyor line.

The results of Test No. 1 suggested the following design changes; (1) elimination of the excess flow valves, and (2) removal of the blast shields protecting the spray nozzles.

2. Test No. 2

The test conditions were similar to those previously outlined except (1) the 60-lb charge was placed at the midway point between two nozzle stations, (2) no excess flow valves were used, (3) the blast shields were removed, and (4) the explosive in the acceptor box was replaced by paper and rags (Figure 21). The water system was "protected" by a 4-in. layer of sand to simulate an actual installation. After detonation the water deluge system did not function. A postmortem indicated the reason for malfunction to be the failure of the explosive valve detonators to function. Examination of the firing circuit revealed that the two detonators were connected in a series; and failure in the first detonator would inactivate the whole system. Based on this information, the electrical circuit for the detonators was modified to provide a parallel rather than series initiation system. No significant damage was sustained by the water delivery system. The only visible effect of the blast appeared to be a slight rotation of one of the spray nozzles located in close proximity to the blast. This rotation would not occur on an installed system where the steel pipe elbow is to be welded in place. No damage was sustained by the UV detector units located 25 ft from the blast. Set on a 6 count discrimination circuit these detectors resulted in a signal to the explosive valve 3-1/2 ms after time-0.

3. Test No. 3

Test No. 3 was conducted immediately after Test No. 2. A box of oil rags was used as an acceptor and placed 8 ft from the nominal 60-lb charge. Since it had been demonstrated that the system could survive a 60-lb blast without damage, about 10 lbs of flake were removed to provide fuel for a later fire suppression test. The water deluge system was fully operational after the detonation and the test was considered a complete success.

Again no damage was sustained by either the water delivery or the fire/blast detection system. The reaction time of the detector system was 3 ms from the time-0. 15 ms after time-0 a pressure in excess of 50 psia was measured 12 ft from the blast valve. Photographic documentation of Test No. 3 included 16-mm motion picture coverage using three cameras, one side-on to the event, and two end-on to the event. Examination of these documentary films supported water pressure data that initially a waterflow was achieved (20 to 30 ms) very rapidly.

Following Test No. 3, a fire fueled by flake Composition-B was set on a wood platform used to simulate a conveyor belt. Approximately 10 lbs of explosive were used for this purpose. The fuel was ignited and allowed to spread until flames several feet high were observed at which time the deluge system was manually actuated. No changes or repairs were made to the water delivery system following the two previous blast tests. Documentary films indicated that the fire was extinguished in less than 1 sec and the water deluge system was fully operational, Figures 22 and 23.

The results of these tests indicate that the basic engineering concepts used for this water deluge system are valid; and it is feasible to develop a rapid-response system capable of withstanding a 60-lb HE blast. A nonvulnerable system can be constructed economically by placing the water delivery piping underground adjacent to the exterior side walls of the building and using narrow stream nozzles. The system tested is capable of very fast response

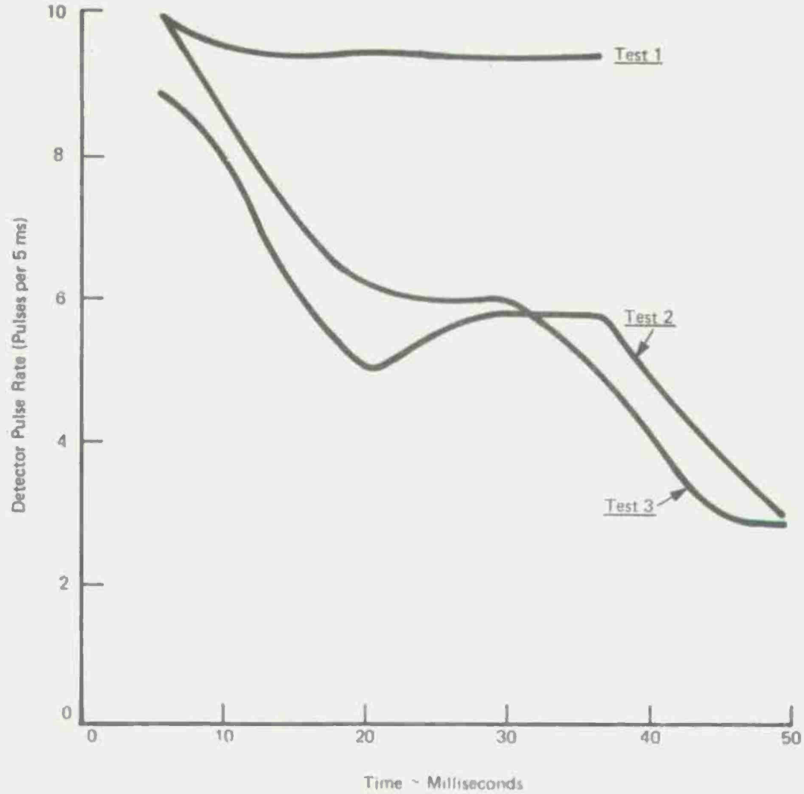


FIGURE 10. UV DETECTOR RESPONSE AT 25-FT LOCATION FOR 60-LB COMPOSITION-B DETONATION–DETECTOR PULSE RATE (PULSES PER 5 MS)

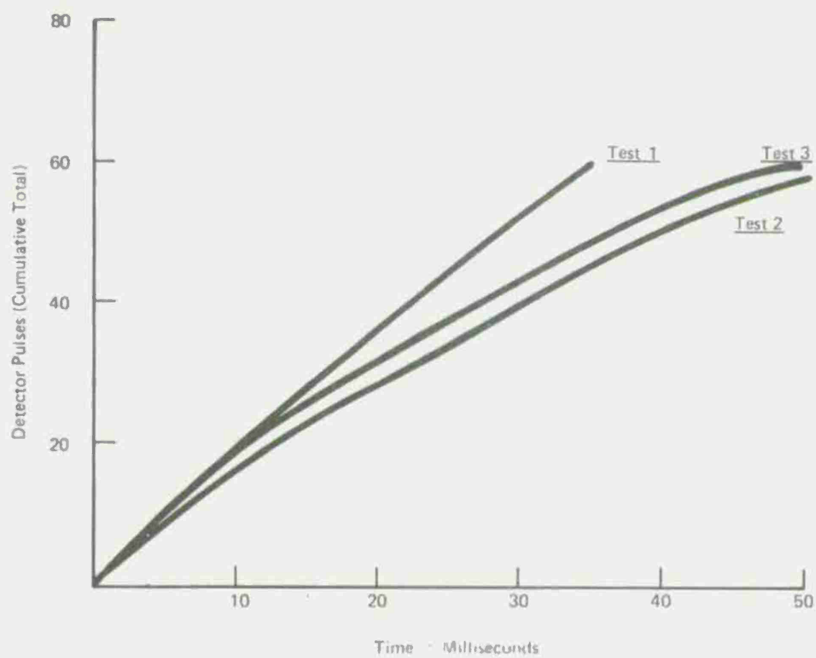


FIGURE 11. DETECTOR RESPONSE AT 25-FT LOCATION FOR 60-LB COMPOSITION-B DETONATION–DETECTOR PULSES (CUMULATIVE TOTAL)

times (20 ms) and has demonstrated its capability to extinguish a large fire after surviving two 60-lb HE blasts. The detector system when located 25 ft from the charge can detect the explosion and activate the water deluge system before arrival of the blast wave (Figures 10 and 11). Based on this feasibility demonstration the following modifications are suggested, (1) parallel circuitry for the detonators to reliably actuate the explosive water valves, (2) reduction or elimination of the blast shields protecting the water delivery system, and (3) elimination of excess flow valves. Further work is needed to optimize the design of this system which represents a major departure from standard fire protection engineering practices. Examination of the detector pulse rate indicates that the useful UV emission from the explosion decreases rapidly after 40 ms. This implies that the detector discrimination circuit must be set to activate the deluge system after a pulse input of less than 50 counts for a 60-lb flake explosive detonation.

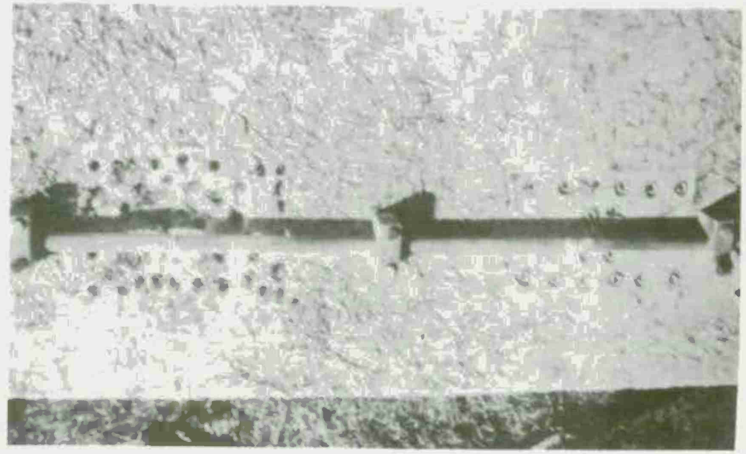
V. CONCLUSIONS

- The feasibility of developing a rapid-response water deluge system capable of withstanding blast effects from a 60-lb HE charge has been demonstrated using off-the-shelf hardware.
- The nonstandard engineering design concepts employed are valid. These concepts include:
    - the use of a floor mounted nozzle spray system;
    - location of spray nozzles at a "safe" distance from the blast area;
    - the use of rupture disk valves to initiate rapid-response water flows.
- The UV detector can detect both explosion and fire events.
- Cost reductions may be effected by developing advanced technology components.

(a) End View Before Explosive Loading

(b) Side View Before Explosive Loading

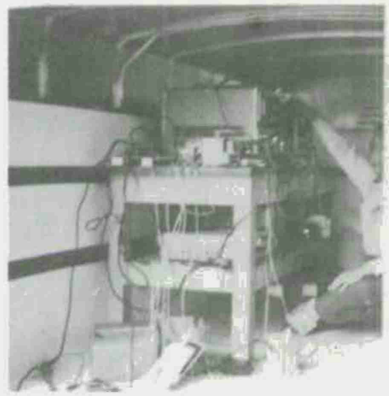
(c) Blast Shields After Explosive Loading



(d) "Schedule 160" Water Pipe After Explosive Loading

FIGURE 12. SCALE MODEL TESTS

(a) U. V. Detector



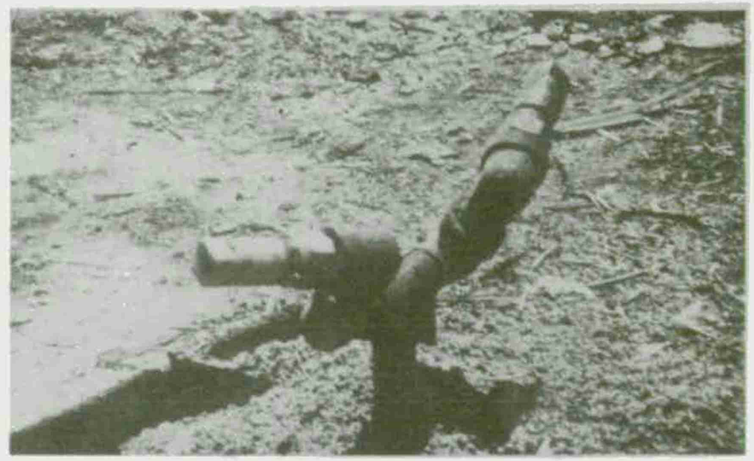
(b) Instrumentation Trailer

(c) Overall View Before Test—First Test Program

(d) Detector Mounting Pole Assembly

FIGURE 13. FIRE DETECTION SYSTEM

(a) Single Nozzle–Second Test Program



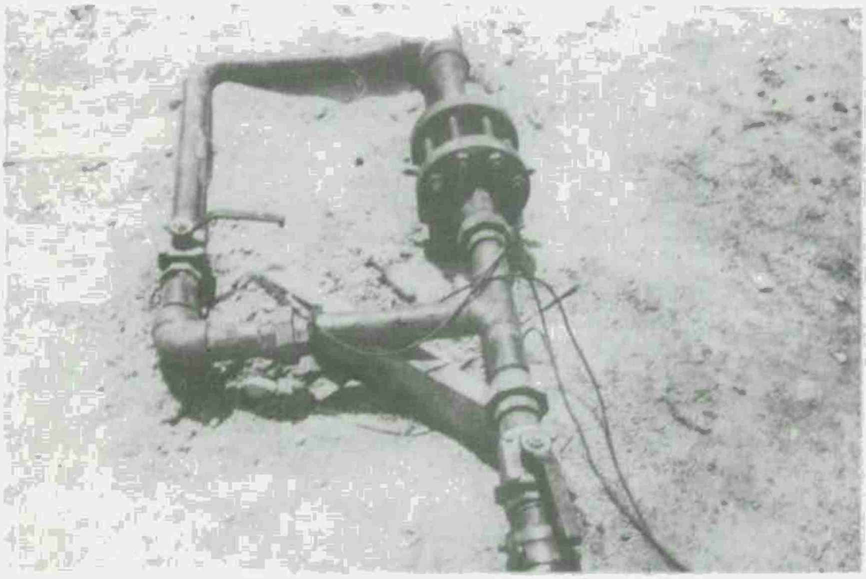
(b) Dual Nozzle–Second Test Program

(c) Water System and Pumper Fire Truck–Second Test Program

(d) Disk Valve and Detonators–After Test

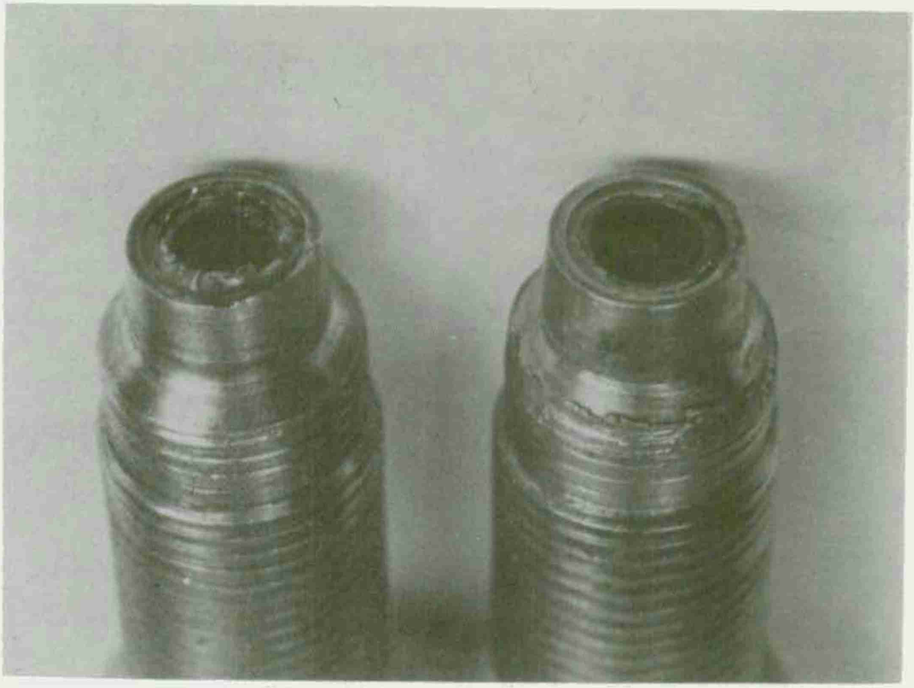
FIGURE 14. WATER DISTRIBUTION SYSTEM

(a) Side View



(b) End View

FIGURE 15. RUPTURE DISK VALVE AND BYPASS VALVE FLOW LOOP



(a) Detonators After Operation

(b) After Operation

FIGURE 16. RUPTURE DISK VALVE

(a) Flake Explosive

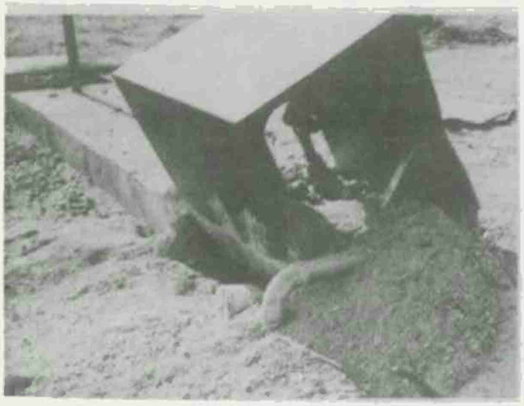
(b) Water Deluge Nozzle—First Test Program

FIGURE 17. DETAIL VIEW OF FLAKE EXPLOSIVE AND WATER DELUGE NOZZLE

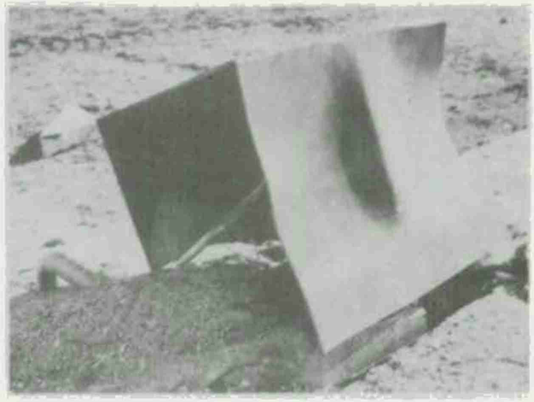
(a) First Test Program

(b) Second Test Program

FIGURE 18. OVERALL FIELD TEST SETUP



(a) Blast Shield Damage—First Test Program

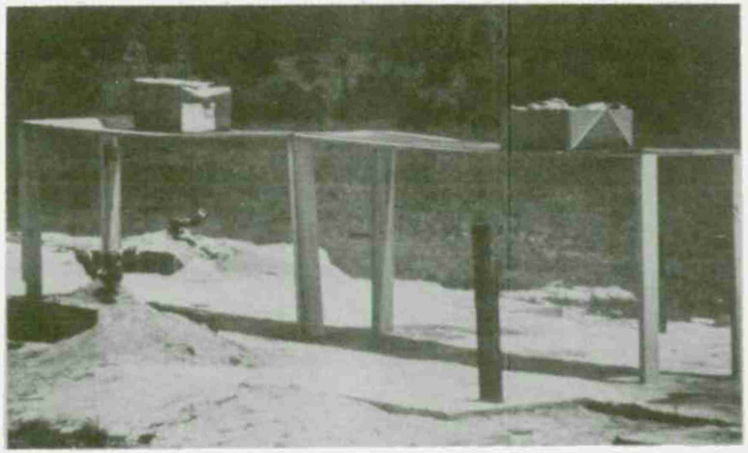


(b) Blast Shield Damage—First Test Program

(c) Overall View of Damage—First Test Program

(d) Water Nozzle Damage—Second Test Program

FIGURE 19. BLAST DAMAGE TO WATER DELUGE SYSTEM



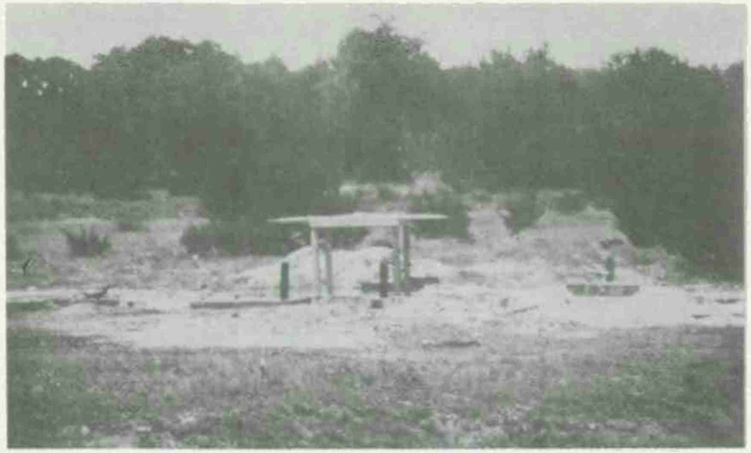
(a) Side View—Second Test Program

(b) End View—Second Test Program

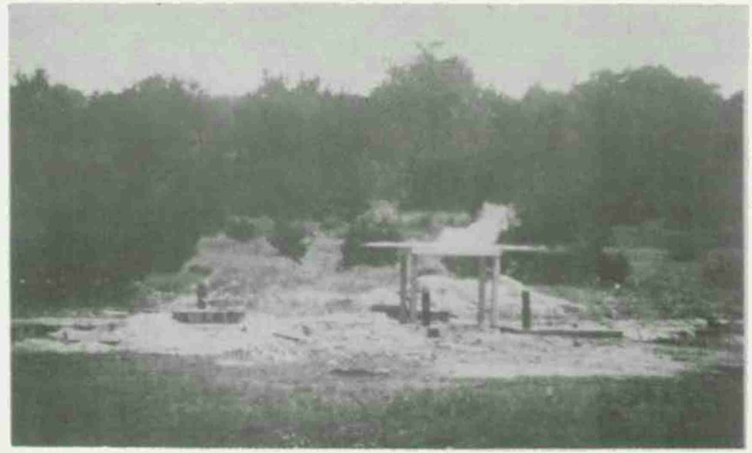
(c) Water Deluge Action After Blast—Second Test Program

(d) Water Deluge Damage After Blast—Second Test Program

FIGURE 20. 60-LB COMPOSITION-B BLAST SURVIVAL TEST FOR WATER DELUGE SYSTEM



(a) Ignition

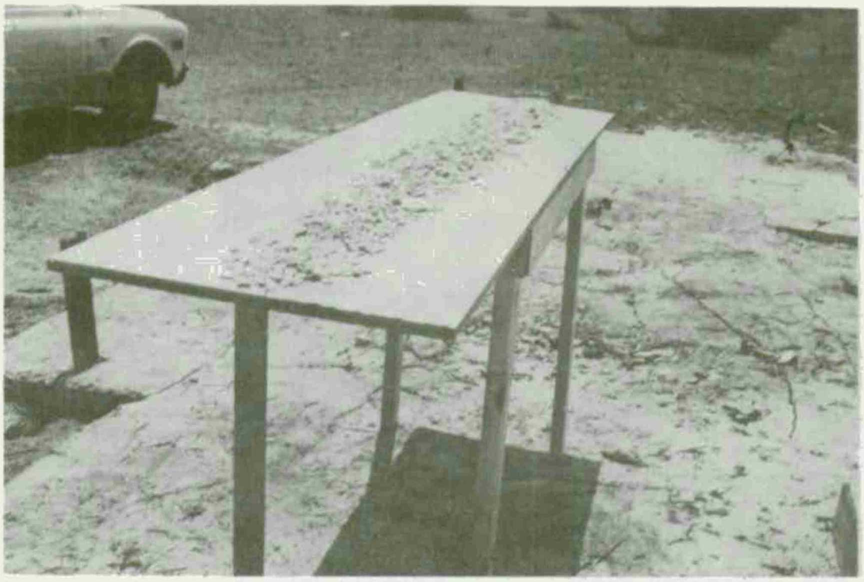


(b) Flame Spread

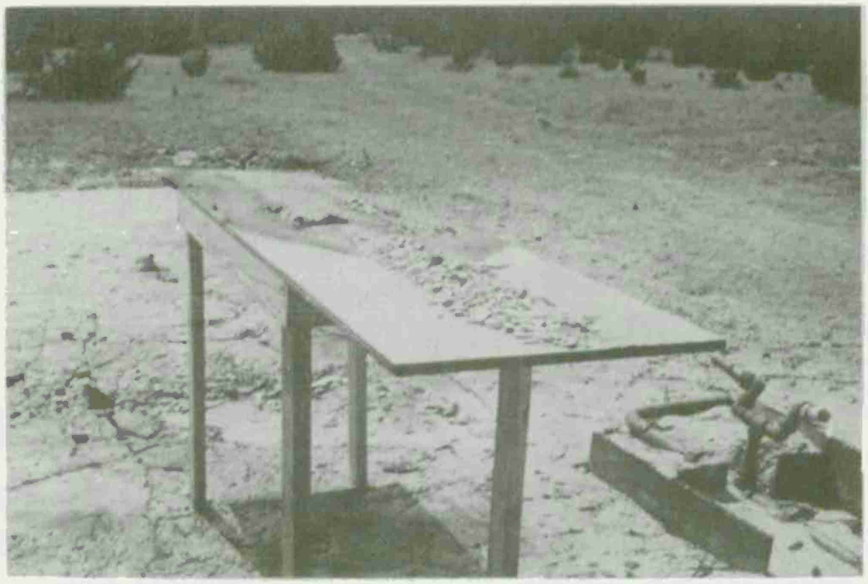
(c) Fire

(d) Water Deluge Action

FIGURE 21. FIRE EXTINGUISHMENT FOR COMPOSITION-B AFTER 60-LB H.E. BLAST SURVIVAL TEST



(a) Before Extinguishment Action



(b) After Extinguishment Action

FIGURE 22. FIRE EXTINGUISHMENT TEST FOR COMPOSITION-B

DISTRIBUTION LIST

	Copy No.
Commander	
Picatinny Arsenal	
ATTN: SARPA-CO	1
SARPA-MT-C	2
SARPA-MT-S	3–17
SARPA-S	18
SARPA-TS-S	19–23
Dover, NJ 07801	
Chairman	24–25
Department of Defense Explosive Safety Board	
Forrestal Bldg., GB-270	
Washington, DC 20314	
Administrator	26–37
Defense Documentation Center	
ATTN: Accessions Division	
Cameron Station	
Alexandria, VA 22314	
Commander	
Department of the Army	
Office, Chief Research, Development and Acquisition	
ATTN: DAMA-CSM-P	38
Washington, DC 20310	
Office, Chief of Engineers	
ATTN: DAEN-MCZ	39
Washington, DC 20314	
Commander	
US Army Materiel Command	
ATTN: AMCSF	40
AMCRD	41
AMCRP	42
AMCIS	43
Eisenhower Avenue	
Alexandria, VA 22333	

Commander
USAMC Installations & Services Agency
ATTN: AMCIS-RI 44
Rock Island, IL 61201

Commander
US Army Procurement Equipment Agency
ATTN: AMX-PE-MT 45
Rock Island, IL 61201

Commander
US Army Materiel Command
ATTN: AMCPM-PBM 46
AMCPM-PBM-S 47
AMCPM-PBM-L 48–49
AMCPM-PBM-E 50–51
Dover, NJ 07801

Commander
US Army Armament Command
ATTN: AMSAR-SF 52–54
AMSAR-SC 55
AMSAR-EN 56
AMSAR-PPI 57
AMSAR-PPI-C 58
AMSAR-RD 59
AMSAR-IS 60
AMSAR-ASF 61
Rock Island, IL 61201

Commander
Edgewood Arsenal
ATTN: SAREA-TD 62
SAREA-MTD 63
Aberdeen Proving Ground, MD 21010

Commander
Frankford Arsenal
ATTN: SARFA-T 64
Philadelphia, PA 19137

Commander
US Army Engineer Division
ATTN: HNDED 65
P.O. Box 1600-West Station
Huntsville, AL 35809

Commander 66
Radford Army Ammunition Plant
Radford VA 24141

Commander 67
Badger Army Ammunition Plant
Baraboo, Wisconsin 53913

Commander 68
Indiana Army Ammunition Plant
Charlestown, IN 47111

Commander 69
Holston Army Ammunition Plant
Kingsport, TN 37660

Commander 70
Lone Star Army Ammunition Plant
Texarkana, TX 75501

Commander 71
Milan Army Ammunition Plant
Milan, TN 38358

Commander 72
Iowa Army Ammunition Plant
Burlington, IA 52601

Commander 73
Joliet Army Ammunition Plant
Joliet, IL 60436

Commander 74
Longhorn Army Ammunition Plant
Marshall, TX 75670

Commander 75
Louisiana Army Ammunition Plant
Shreveport, LA 71130

Commander 76
Cornhusker Army Ammunition Plant
Grand Island, NB 68801

Commander 77
Ravenna Army Ammunition Plant
Ravenna, OH 44266

Commander 78
Newport Army Ammunition Plant
Newport, IN 47966

Commander 79
Volunteer Army Ammunition Plant
Chattanooga, TN 37401

Commander 80
Kansas Army Ammunition Plant
Parsons, KS 67357

District Engineer 81
US Army Engineering District, Mobile
Corps of Engineers
P.O. Box 2288
Mobile, AL 36628

District Engineer 82
US Army Engineering District, Ft. Worth
Corps of Engineers
P.O. Box 17300
Ft. Worth, TX 76102

District Engineer 83
US Army Engineering District, Omaha
Corps of Engineers, 6014 US PO & Courthouse
215 N 17th Street
Omaha, NB 78102

District Engineer 84
US Army Engineering District, Baltimore
Corps of Engineers
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Baltimore, MD 21203

District Engineer 85
US Army Engineering District, Norfolk
Corps of Engineers
803 Front Street
Norfolk, VA 23510

Division Engineer 86
US Army Engr. Dist. Huntsville
P.O. Box 1600
West Station
Huntsville, AL 35807

Commanding Officer 87
Naval Ordnance Station
Indianhead, MD 20640